Experimental Investigation on Mechanical Properties of High-Performance Concrete and Effect of Modulus of Elasticity and Poisson's ratio

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Abstract:
This experimental study examines the mechanical properties of High-Performance Concrete (HPC) incorporating a substantial proportion of mineral admixtures. Using high-performance concrete in the construction of multi-story structures provides enough benefits to justify consideration as a practical and desirable choice. The significance of research contributions in providing technical exposure to this minor component will become clear as the use of HPC grows in popularity. The method proposed by P. C. Aitcin is used to calculate the mixed proportion of HPC 60 MPa to 80 MPa. Studies are done on the characteristics of the various ingredients used to make HPC. Thirteen concrete mix compositions were evaluated thoroughly, including mechanical properties such as compressive strength, split tensile strength, modulus of elasticity, and flexural strength, as well as an assessment of significant properties. The outcomes of this investigation affirm that a reduced water-to-binder ratio (w/b) correspondingly leads to enhanced mechanical properties. For the purpose of examining the physical properties of various concrete grades, a total of 39 cubes, 39 cylinders, and 39 beams were cast. HPC cubes were tested on a compression testing machine with a loading capacity of 3000 KN, while cylinders and beams were tested on a universal testing machine with a loading capacity of 1000 KN. The average compressive strength for HPC M60 to M80 is 61.46 MPa, 71.35 MPa, and 80.10 MPa, respectively. Elastic Modulus values obtained in the present study range from 40 and 50 GPa. The findings of the present study suggest that an enhancement in concrete strength correlates with a reduction in the average value of Poisson's Ratio. Overall, the choice to use HPC for high rise structure offers sufficient advantages to benefits consideration as a cost-effective and attractive alternative. The significance of research contributions in offering proper guidance on this new concrete material becomes clear once the material of HPC becomes widely used.
Keywords: High-Performance Concrete, Compressive Strength, Flexural Strength, Split Tensile Strength, Elastic Modulus, Poisson's Ratio.

1. INTRODUCTION:

Investigation into HPC is mainly focused on various three areas. The primary area gives detailed investigations of the basic structure of HPC materials [Tayeh, B. A. et. al. 2020]. The components of concrete together including the moment interaction between them investigate the properties of the ensuing material. A phenomenon mentioned on the micro-scale, such as hydration of the cement, micropores content along with interface effect among cement pastes along with aggregates, help to understand together including the factors that make the material strength to develop [Shi, T., Li, Z., et. al. 2022]. Studying engineering properties of high-performance concrete constitute another area of research, which includes, Poisson's ratio, compressive strength, ultimate tensile strength along with elastic modulus [Shafieifar, M. et. al. 2017]. The third investigation area is related to the properties of HPC which impacts the behaviour of the structure. The point of interest is given on HPC along with its impacts on distinct strengthened concrete elements inclusive of columns [Akeed, M. H. et. al. 2022]. The research study focuses mainly on the third category of the behaviour of reinforced log columns, with the main emphasis on design-related studies. Some part of the study is also lined with different physical properties of HPC. At present due to taking less space and saving in materials in columns of high-rise structures along with bridges, the use of HPC is increasing [Abdal, S., et. al. 2023]. However, more important the value for the strength of concrete motivates designers to minimise the cross-section of structural elements considering the same ultimate strength of the section and along with the slenderness ratio of the reinforced long column is increased [Aboukifa, M. et. al.2022]. As the usage of HPC increases in popularity, the need of research in providing technical details on this new material becomes prominent [Byrne, G et al. 2016]. The use of high-performance concrete (HPC) in the construction of high-rise structures gives significant benefits that justify investigation as a cost-effective and attractive choice [Amran, M., et al. 2022]. The development of HSC is attributed to Yoshida, who used high-strength compaction to create concrete with a strength greater than 96 MPa. HPC gives special performance along with consistency desires that can't always be achieve habitually using regular materials and standard mixing, placing and curing practices. Today, high strength long RC columns have become more and more accepted in the construction business. [Wu, Z., et. al. 2014]. Such a concrete can neither be normal strength concrete or high strength concrete. The long-term functionality of structures now determines the economic health of all nations.

Concrete has been an essential part of building maintaining and reliable infrastructure since the time of the Greek and Roman civilizations. When considered together, the choice to use high-performance concrete in the design of high-rise buildings offers a wealth of benefits, positioning it as a wise choice from both an aesthetic and financial standpoint. Overall, the choice to use HPC for high rise structure offers sufficient advantages to benefits consideration as a cost-effective and attractive alternative. The significance of research contributions in offering proper guidance on this new concrete material becomes clear once the material of HPC becomes widely used [Lim, J. et. al. 2019].

2. LITERATURE REVIEW:

The French should be given credit for coining the phrase "High-Performance Concrete." It was first used by Roger Lacroix and Yves Malier in 1980. 36 journals spanning France, Switzerland, & Canada were gathered together in 1986 by the French initiative in terms of new ways for Concrete. Pierre-Claude Aitcin served as the group's leader from Canada. The first book was published by all members and is totally devoted to HPC (High Performance Concrete) related to research, outcomes and its application in the field.

Pierre-Claude Aichin built a productive network of centers of excellence for HPC, supported by the Federal Government's Centers of Innovation Program, before the end of 1988 with the help of Dennis Mitchell and Michael Collins. The second phase of this work started 1994, and the network became known as concrete Canada. This research programme started in 1990. Numerous studies on the topic were conducted as well as thousands of publications were printed between 1990 to 2000. Many nations in Europe, Asia, Australia, Japan, and North America run extensive research projects on HPC. Now a days HPC gained a lot of popularity. Many large cities and the majority of state highway authorities have adopted or are in the phase of adopting its uses. As a result, several consultants add it to their specifications, which leads to numerous subcontractors receiving assignments that have good scope for development.

a. AASHTO/ASTM

In the AASHTO and ASTM codes, conversion coefficients are furnished to assess strength test outcomes in cases where the h/d ratio is below 1.8. These coefficients serve to transform strength test outcomes into commensurate results for specimens with an h/d ratio of 2. Typically, these coefficients find application in tests conducted on cores extracted from structures [De Brito, J. et. al. 2016]. The values of these coefficients for varying h/d ratios are detailed in Table 1.

Table 1 Values of factor as per AASHTO/ASTM

h/d	1.75	1.5	1.25	1.00
Factor	0.98	0.96	0.93	0.87

b. UNESCO

The UNESCO manual on reinforced concrete offers conversion coefficients tailored to specimens of different dimensions and configurations [Liu, T. et. al. 2021]. The conversion factors suggested by UNESCO are outlined in Table 2.

Table 2 Factors recommended by UNESCO

Specimen Shape	Specimen Size in mm x mm	Conversion factor
Cylinder	150 × 300	1.00
	100 × 200	0.97
	250 × 500	1.05
Cube	100 × 100 × 100	0.80
	150 × 150 × 150	0.80
	200 × 200 × 200	0.83
	300 × 300 × 300	0.9

c. Naville's equation

In 1966, Naville synthesized data from numerous prior investigations to formulate a comprehensive correlation encompassing compression test specimens of diverse shapes and dimensions. The resulting relationship, as presented below, was documented [Soutsos, M. N. et. al. 2012].

$$\frac{P}{P_6} \times \frac{d}{d_6} = 0.8878 \left(\frac{A}{A_6}\right)^{0.4525}$$

Where,

d_6	=	A 150 mm cube's greatest lateral dimension
A	=	cross-sectional area, and
A_6	=	a 150 mm cube's cross-sectional area
P/P_6		ratio of cylinder strength to cube strength

d. L'Hermite's equation

Back in 1955, R.L'Hermite put forth a straightforward equation that established the cylinder/cube strength ratio in relation to the cube strength.

$$\frac{Cylinder\ strength}{Cube\ strength} = 0.76 + 0.2\, log_{10} \frac{f_{cu}}{2840} \quad .... \quad (2.1)$$

where f_{cu} cube strength in psi.

The findings of certain researchers in the literature regarding the cylinder to cube ratio are depicted in Table 3.

Table 3 Some results of cylinder vs. cube comparative studies

Reference	Average cylinder/cube ratio	Remarks
Cormack	0.87	The research concentrated on high-strength concrete.
Evans	0.77-0.96	Lower strength concretes have a lower cylinder/cube strength ratio in general
Lysle and Johansen	0.86	-
Gonnerman	0.85-0.88	Standard cylinders of 150 mm x 200 mm were used in the tests.

Based on a widespread survey of previous research work, a subsequent general conclusion can be drawn. Higher-strength concretes are much more brittle than traditional normal-strength concrete because strength and ductility are inversely associated with one another. As a result, for higher-strength concrete columns, concrete confinement becomes an essential concern. Published data on the large-scale higher strength concrete reinforced concrete structures up to 80 Mega Pascal are scarce. The present study includes a thorough assessment of various reinforced concrete components as well as the determination of fundamental mechanical properties like compressive strength, tensile strength, and elastic modulus. The formulation of equations for various parameters will be presented, followed by a comparison with already-formulated equations. The failure patterns of concrete cubes and cylinders of conventional strength will be compared to those of concrete of higher strength. In addition, possible differences between the failure patterns shown by cubes and cylinders may be analyzed.

3. METHODOLOGY:

Mix proportion is the procedure of evaluating the right combination of ingredients to prepare a homogeneous cement concrete mix with the required properties at a very low probable cost. Although regular normal concrete, the progression is cumbersome as various conflicting requirements must be balanced.

3.1. Selection of Ingredients for HPC:

HPC manufacturing is a more complex process than normal concrete due to a number of parameters to be managed to become more important two mineral admixtures and superplasticizers. It is required to have bond between cement and superplasticizer so that they form a liquid mixture and remain in liquid form for a long period to place easily. Throughout the entire examination, OPC of 53 grades (Ultratech cement), which is commercially available and confirms relevant IS code (IS 12269-1987), was used. Improved strength development functionality Cement grades 43 and 53, which conform to IS 8112-1989 and IS 12269-1987, respectively, are now available in India. Depending upon the strength and durability necessities the sort of cement can be selected to achieve economy in the mix proportions. In this experimental research crushed basalt stone in the form of small pieces are used as coarse aggregates. The maximum size of aggregate was 20mm down to produce 60 Mega Pascal to 80 Mega Pascal and 12mm down for 100 Mega Pascal to 120 Mega Pascal. Sand mixed stock that passes through a 75-micron sieve and have a silt content by weight are considered to be silt. This silt makes concrete less workable, increases the W/C ratio, and decreases strength. Sand available from Krishna River was used for entire testing. The sand that was applied fits into grading zone III of table 4.IS:383-1970. Elkem material were provided the silica fume which required for this experimental work. Microsilica is one in every of the goods furnished by resources of Elkem materials. Metakaolin is the best and most efficient mineral admixture that can partially replace to cement in concrete production. The chemical formula of metakaolin is AL2O3. 2SiO2. 2H2O.

To keep the required workability of HPC, the water content will be reduced using superplasticizers. Master Glenium Sky 8654 is use as a strong water reducer. This is where Glenium B233 differs from conventional super plasticizers. so far, they have been mostly based on unique carboxylic ether polymers with long polymer chains. What differentiates Glenium products apart from traditional super plasticizers is a new, unique mechanism of action that significantly progress the effectiveness of distribution.

Customary superplasticizers based entirely on melamine and naphthalene suffocates are polymers that can be absorbed through cement granules. According to IS 456-2000 article 4.3, water added for mixing of concrete and used for curing purposes must be free from potentially harmful substances. Uses potable water with a pH of between 7 and 7.5. The clause also stipulates that the pH level cannot be lower than 6. In this study, the only potable tap water available in the lab was used. After carefully considering the literature suggestions and conducting an analysis, we have opted to utilize HPC ingredients that fulfil the required properties. Based on that Table No. 4 shows the properties of selected ingredients.

Table 4 Materials used with their properties.

Cement	
Grade of Cement	OPC, 53 Grade, Ultratech
Specific gravity of cement	3.15
Coarse Aggregates (CA)	
Specific Gravity of CA	2.95
Maximum and Minimum size of CA	16mm & 10mm
Impact Value of CA	18.60%
Water Absorption	2.52%
Bulk Density of CA	2087 kg/m^3
Crushing Value of CA	16.70%
Fine Aggregates (FA)	
Specific Gravity of FA	2.88
Bulk Density of FA	1640 kg/m^3
Silt Content	3.75%
Water Absorption	3.55%
Fineness Modulus of FA	2.60
Superplasticizer	
Brand Name	Master Glenium Sky 8654
Specific Gravity	1.10
Producer Company	BASF
Specifications for reference	IS 9103:1999
Solid Content	33%
Silica Fume (SF)	
Specific Gravity SF	2.15
Fly Ash	
Specific Gravity Fly Ash	2.10
Consumable Water	
P^H	7.0-7.6

3.2 Design Mix of HPC from M60 to M80:

HPC shows very low porosity and the strongest transition zone results in great durability and strength characteristics. In HPC, minimizing water content from the concrete also maintaining the required workability is prime important and is achieved by adding superplasticizers. using the method suggested by P. C. Aitcin, the concrete of strengths 60 Mega Pascal to 80 Mega Pascal were produced by using ingredients like fine aggregates (locally available river sand), coarse aggregates (crushed stone chips), OPC cement of 53 grade, mineral admixtures (Fly ash and Silica fume) and superplasticizer (Master Glenium 233). The final design mix proportion for 60Mpa to 80Mpa is as shown in Table 5.

Table 5 Design Mix for HPC M60 to M80

Materials	Compressive Strength in MPa		
	60	**70**	**80**
W/C	0.44	0.39	0.36
Cement, kg/m^3	366	405.11	441
Fine Aggregate, kg/m^3	693.24	654.90	615.78
Coarse Aggregate, kg/m^3	1087.79	1087.79	1087.79
Water, kg/m^3	162.63	158.23	157.24

Metakaolin, kg/m^3	---	----	----
Fly ash or silica fume kg/m^3	91.42	101.29	110
HRWR (Master Glenium Sky 8654) in %	0.4	0.42	0.45

Concrete mix design (proportioning) consists of different steps to calculate the desired proportion of required materials which will produce a mixture with the appropriate properties at very minimum possible cost. High-performance concrete is produced with proper selection of different ingredients. To develop and control the rheology of designed concrete, the mechanical and chemical properties of cement are prime important. Water requirements for the consistency of fresh concrete are affected by the fineness of the cement. In HPC, cement strength and bond strength may exceed the strength of the aggregates. Hence high strength aggregates used in concrete can lead to a remarkable increase in the strength of concrete. The particle size distribution and shape of particles of fine aggregates are important factors in the manufacturing of HPC. The form and texture of the particles have a considerable impact on the water-cement ratio and compressive strength of the concrete produced. River sand and crushed stones are utilised as fine and coarse aggregates in the production of HPC.

4. EXPERIMENTAL WORK:

The great difference between traditional cement concrete and HPC is that high-performance concrete consists of mineral admixtures in the matrix. HPC shows very low porosity and the strongest transition zone results in great durability and strength characteristics. In HPC, minimising water content from the concrete also maintaining the required workability is prime important and is achieved by adding superplasticizers. The selected superplasticizers should have more solid content and specific gravity and a longer molecular chain length for better efficiency. The concrete of strengths 60 Mega Pascal to 80 Mega Pascal was produced by using ingredients like fine aggregates (locally available river sand), coarse aggregates (crushed stone chips), OPC cement of 53 grade, mineral admixtures (Fly ash and Silica fume) and superplasticizer (master Glenium 233) using the method suggested by Aitcin.

To study the mechanical characteristics of cubes, cylinders, and beams, a Compression Testing Machine (CTM) with a capacity of 3000 kN and a Universal Testing Machine (UTM) with a capacity of 1000 kN are utilised. After 28 days, three tests were performed: flexural strength, split tensile strength, and compressive strength, as shown in Fig. 1.

Fig. 1 Testing of cubes and cylinders to access mechanical properties

HPC properties that are equivalent to HSC (high strength concrete) are difficult to believe. The improvement in compressive strength of high-performance concretes is largely dependent on a minimal W/C (water/cement) ratio than on mineral admixtures, such as silica fume, being replaced with cement. The compressive strength will be substantially greater if silica fume content is replaced up to 20% and reaches a maximum for a 10 to 15% silica fume amount. However, the maximum strength gain over high performance concrete is less than 15%. Tables 6, 7, and 8 demonstrate the compressive strength, flexural strength, and split tensile strength of concrete grades M60 to M80.

Table 6 M60 concrete's compressive strength, split tensile strength, and flexural strength

Sr. No.	Max. Load (kN)	Strength in (N/mm^2)	Average strength (N/mm^2)	28 days Strength As per ACI code in N/mm^2	28 days Strength according IS code in N/mm^2	28 days Strength according Literature
Compressive strength						
1	1372 1398 1379	60.97 62.13 61.28	61.46	70.82	60	64.06
FS (Flexural Strength)						
2	10.20 10.96 10.44	5.10 5.48 5.22	5.26	4.80	5.42	7.20
Split Tensile Strength						
3	290 285 296	4.10 4.03 4.18	4.10	4.06	4.64	4.10

During the test, the kinds of failure and cracking properties of two types of concrete specimens (cubic and cylindrical) for various concrete mixture strengths were observed. The fracture process can be utilised by a stress concentration at the cube corners in the case of cubes. At the corners, incline micro-cracks appear and become dense. Crushing produces vertical cracks and column-like fragments as the load increases.

Table 7 M70 concrete's compressive strength, split tensile strength, and flexural strength

Sr. No.	Max. Load (kN)	Strength in (N/mm^2)	Average strength (N/mm^2)	28 days Strength As per ACI code in N/mm^2	28 days Strength according IS code in N/mm^2	28 days Strength according Literature
Compressive strength						
1	1610 1630 1577	71.55 72.44 70.08	71.35	70.82	70	73.44
FS (Flexural Strength)						
2	11.04 11.66 11.51	5.52 5.83 5.75	5.70	5.18	5.85	5.72
Split Tensile Strength						
3	320	4.52	4.54	4.42	5.01	4.10

327	4.62
318	4.50

The first crack in NSC was discovered to form at small stress levels up to 40% of the ultimate load. In HPC, the first cracking occurred at up to 70% of the ultimate load, the number of cracks on against faces developed at around 85%, and the corners ultimately cracked at around 95% of the maximum stress level.

Table 8 M80 concrete's compressive strength, split tensile strength, and flexural strength

Sr. No.	Max. Load (kN)	Strength in (N/mm²)	Average strength (N/mm²)	28 days Strength As per ACI code in N/mm²	28 days Strength according IS code in N/mm²	28 days Strength according Literature
Compressive strength						
	1798	79.91				
1	1803	80.13	80.10	92.82	80	88.9
	1806	80.26				
FS (Flexural Strength)						
	11.96	5.98				
2	12.10	6.05	6.01	5.54	6.26	5.60
	12.02	6.01				
Split Tensile Strength						
	341	4.82				
3	349	4.93	4.83	4.76	5.36	5.40
	336	4.75				

Study of some mechanical properties is also important for design of reinforced concrete members. Based on the experimental data of present study, relation between cylindrical strength and compressive strength of HPC is drafted as shown in Fig. 2. The proposed analytical equations are compared with the equations in the literature and codes and their suitability was discussed.

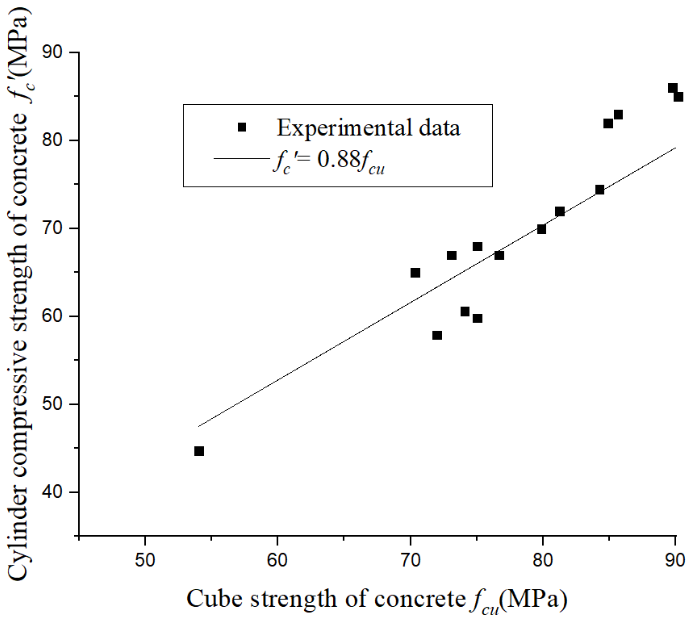

Fig. 2 Relation between cylinder strength and cube compressive strength of HPC

It is critical for accurately determining the relationship between concrete cylinder strength and cube strength. However, researchers have tried to relate them analytically and experimentally. The stronger the concrete, the superior the ratio. Fig. 3 demonstrates the conversion factor (cylinder-to-cube strength ratio). For the normal strength concrete conversion factor is decided to be 0.8 up to strength 60 Mega Pascal concrete and 0.85 for strength 80 Mega Pascal onwards.

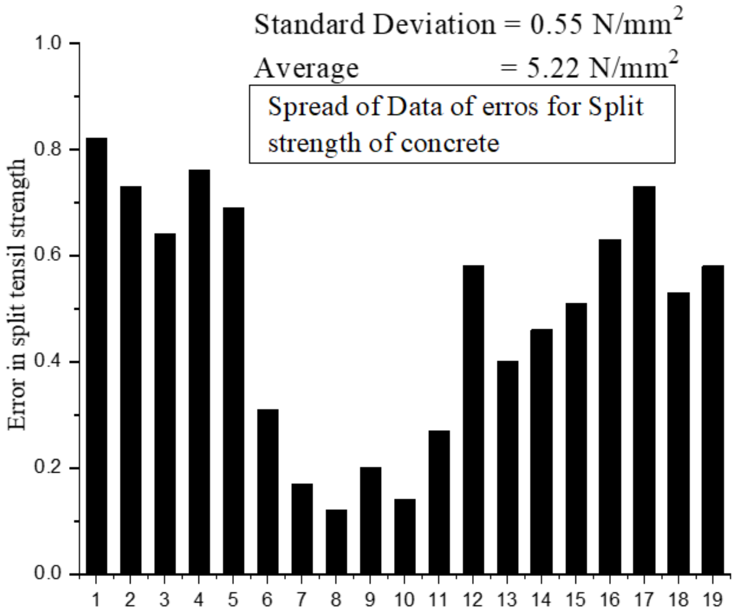

Fig. 3 Relation between compressive strength of concrete and split tensile strength and error bars to indicate spread of data

Fig. 4 Ultimate Cracking pattern of Cubes

Fig. 5 Inclined fracture surface and diagonal fracture zone for cylinder

A simple inspection indicates that the impact of giving in the specimens was greater in the cubes than in the cylinder. The inclined fracture surface and diagonal fracture zone for cylinder is as shown in Fig. 5. According to the latest research, the initial crack in HPC cylinders appeared at about 85% of the ultimate stress, but as greater force was applied, the same split failure continued and eventually failed with a smaller number of cracks.

5.0 RESULT & DISCUSSION:

5.1 Mechanical Properties of HPC

The mechanical properties of hardened concrete are the most important features to civil engineers and anybody working with concrete. Compressive strength, modulus of elasticity, and tensile strength are examples of these properties. The compressive strength of concrete that has been hardened is its most significant property since all other concrete strengths, such as tensile, flexural, shear, and bond strength, are all related to it. As a result, high compressive strength concrete will have improved additional properties.

The modulus of elasticity is the property that explains the elastic behaviour of concrete. The modulus of elasticity is significant in the design of flexural members because it defines the concrete's contribution to the member's flexural rigidity. In the pre-peak zone, the stress-strain relationship of concrete exhibits non-linear behaviour. Therefore, determining the elastic modulus of the material is challenging. That is why there is no widely accepted definition. Elastic modulus defined as it relates to the chords drawn at different stress levels were utilised by different codes and researchers. The chord described at 45% stress level was proposed in ACI 318-08. Several standards accept a similar notion, but with the reference point set at 40% of the strength (ASTM C469-87) [Gencel, O. et. al. 2011], Erocode-2, and Australian Standard AS 1012.17-1997 [Wardhono, A. et. al.], as well as by other writers for HPC.

The tensile strength of concrete structures that fail in compression is more likely to be exceeded before the concrete collapses in compression. Typically, the value of tensile strength is not considered in design, which is with the assumption that the reinforcement alone can bear all tensile stresses. The rupture modulus is seen to be the best technique to explain the members' flexural behaviour. Raphael noted that the results are around 50% higher than the prior two tests. According to the same source, this is the result of the nonlinear properties of the stress-strain diagram of concrete under tension, as well as an improper use of elastic theory to calculate the modulus of rupture [Bliuc, R. et. al. 2004].

The lateral strain to linear strain ratio in the loading direction is defined as Poisson's ratio. Poisson's ratios range from 0.15 to 0.25. A lower Poisson's ratio indicates brittleness in a greater strength concrete. HPC is currently commonly used in bridges and other constructions. Current code standards for reinforced concrete members, such as the IS 456-2000, are, however, mostly based on empirical relationships obtained through testing normal-strength concrete. When equations created using NSC are applied to HPC members, these highlights relate to that the design may not be appropriate. In contrast, the equations may be excessively sensitive, which leads to the benefits of implementing HPC not being completely utilised. As a result, more study is needed to establish a significant correlation between HPC's specified design compressive strength (specified design fc') and related splitting tensile strength ft, modulus of rupture fr, and modulus of elasticity Ec.

5.2 Compressive strength of concrete

It is incorrect to believe that the mechanical properties of HPC are simply those of a stronger concrete. It is also wrong if you think that the mechanical properties of HPC can be calculated by developing those of conventional concretes, just as it is wrong for claiming that none of them are linked together. HPC has a more compact microstructure, including the transition zone with coarse aggregate, resulting in a small or non-existent transition zone. As a result, the mechanical properties of coarse aggregate impact parts of the mechanical properties of HPC. This is because, when crushing a particular rock, the smallest pieces are often stronger than the coarsest since they include fewer cracks. This is known as the "size impact phenomenon."

In general, NSC (Normal Strength Concrete) and HPC (High Performance Concrete) behaviour may be classified as follows: NSC is homogeneous and isotropic, with the weakest points often situated in the hydrated cement paste or the transition zone. Clearly, the characteristics of the ingredients as well as the water-to-binder ratio impact the distinctive properties of this composite material. Table 5.1 shows the results of compressive testing on both cubic and cylindrical specimens.

5.2.1 Crack Pattern

Cracking is an essential component in the behaviour of a heterogeneous material such as concrete, and the development of micro-cracking is highly related to interfacial transition zone parameters. Because of advancements in concrete microstructure, the mechanism of failure of HPC specimens in uni-axial compression varies from that of NSC specimens. As compressive strength increases, the amount and intensity of continuous series of cracks developed at rupture decrease. Cracking in HPC is more confining than cracking in NSC and matches the behaviour of a homogenous material. Cracks are frequently found to occur between the aggregate and cement paste surfaces in NSC. Cracks spread through both the aggregate and the paste in HPC, resulting in lower resistance throughout the surface area.

Table 9 Mechanical properties of high-performance concrete

Grade of Concrete in MPa	Cube Strength f_{cu} in N/mm^2	Cylindrical Strength f_c' in N/mm^2	Elastic Modulus E_c in GPa
60	75.83	62.00	40.40
60	73.86	70.90	41.84
60	76.51	68.00	40.20
60	74.10	65.00	40.43
60	77.63	66.71	38.18
70	78.83	67.00	42.40
70	80.86	70.90	44.84
70	79.51	68.00	42.20
70	80.10	67.00	44.43
70	78.63	70.71	43.18
80	83.85	77.58	45.42
80	93.65	88.00	45.05
80	82.35	74.36	45.47
80	88.89	78.00	44.61
80	90.87	82.00	45.27

A stress concentration at the cube corners initiates the fracture process in the case of cubes. As seen in Fig. 5.1, incline microcracks create and connect within the corners. Crushing produces vertical cracks and column-like material as the load increases, as shown in Fig. 5.2. The first crack in NSC was discovered at a very low stress level, about 40% of the ultimate load. As shown in Fig. 5.1, the first cracking developed in HPC at about 70% stress level, the number of cracks developed on against faces at around 85% stress level, and eventually the corners collapsed at around 95% stress level. In smaller specimens (100 mm x 100 mm x 100 mm), the cracking was the same, except that the initial cracking was generated at a higher stress level, about 75%, resulting in a higher compressive strength of concrete. Finally, as seen in Fig. 6 the cubes crush.

A brief visual inspection shows that the cubes damaged more than the cylinders. As illustrated in Fig. 7 and Fig. 8. cylinders formation a first inclined fracture surface, and all cylinders subsequently separated together to form a diagonal fracture plane, as shown in Fig. 9 and Fig. 10. The initial crack in HPC cylinders was seen to occur at approximately 85 percent of ultimate stress in the current investigation, and additional loading propagates the same crack, getting started the failure with fewer cracks.

Fig. 6 Coalescence of cracks near the corners

Fig. 7 Vertical Cracks leading to Column fragments

Fig. 8 Ultimate Cracking pattern of Cubes

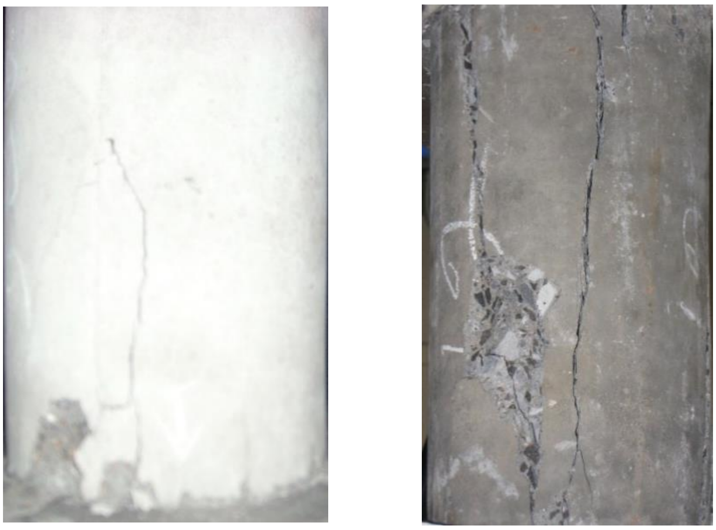

Fig. 9 Nucleation of inclined fracture surface and diagonal fracture zone

Fig. 10 Ultimate Cracking pattern of cylinders

5.3 Tensile strength of concrete

Concrete has a comparatively high compression strength but a low-tension strength. Because reinforcement is given to resist all tensile stresses, reinforced concrete members place not much value on the tensile strength of concrete. Tensile stresses within concrete exhibit heightened sensitivity to various factors such as drying shrinkage, corrosion of reinforcement, temperature discrepancies, and a range of other variables. Consequently, possessing a comprehensive understanding of concrete's tensile strength assumes paramount importance. The assessment of concrete's tensile strength is conducted through two prescribed tests outlined as follows:

1. Split Tensile Strength Test
2. Flexure Strength Test

5.3.1 Split tensile strength

It is also referred to as the indirect tension test method. The "Brazilian Test" is another name for this. In 1943, Brazil created this test. This was separately created in Japan around the same time. This test is performed by inserting a cylindrical specimen horizontally between the loading surfaces of compression testing equipment and applying a load along its vertical length until the cylinder fails. Table 9 displays the test results.

The key benefit of this procedure is that it may utilise the same specimen and testing apparatus as the compression test. As a result, this type of examination is becoming increasingly common. The split tensile strength test is characterized by its relative simplicity in execution and its capacity to generate results of greater precision compared to alternative tension testing methods. The configuration of the cylinder subjected to the split tensile strength test is illustrated in Fig. 11. Notably, the split tensile strength is acknowledged for its closer alignment with concrete's authentic tensile strength in contrast to the modulus of rupture.

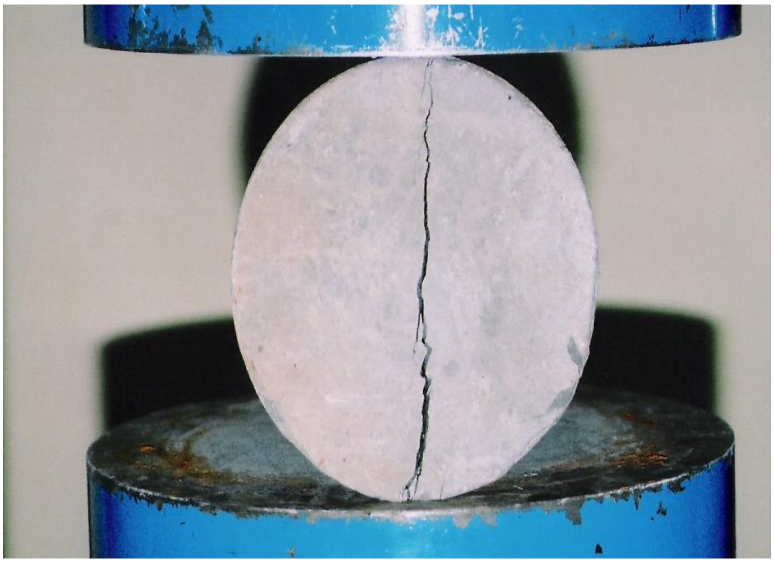

Fig. 11 Cylinder tested for split tension test

As illustrated in Fig. 11, an empirical relationship for split tensile strength has been established.

$$f_{t1} = 0.565\sqrt{f_c'}\, inMPa \quad .... \quad (1)$$

$$f_{t2} = 0.536\sqrt{f_{cu}}\, inMPa \quad .... \quad (2)$$

As demonstrated in Fig. 5.8, Eq. 5.1 can be compared to the analytical equations presented by ACI 363 [3], Ahmed and Shah [04], Bhanja and Sengupta [08], Irvani Said [19], Mary Beth [97], and Selim Pul [28]. The method of calculating suggested by Selim Pul [28] is only valid for concrete strengths up to 80 MPa. The proposed equation in this work matches that of Bhanja and Sengupta and is also extremely close to those of Said Irvani [19], ACI 318-08, and Mary Beth [37]. However, the split tensile strength is overestimated by the formulae ACI 363R [1, Ahmed and Shah [04], and Selim Pul [28].

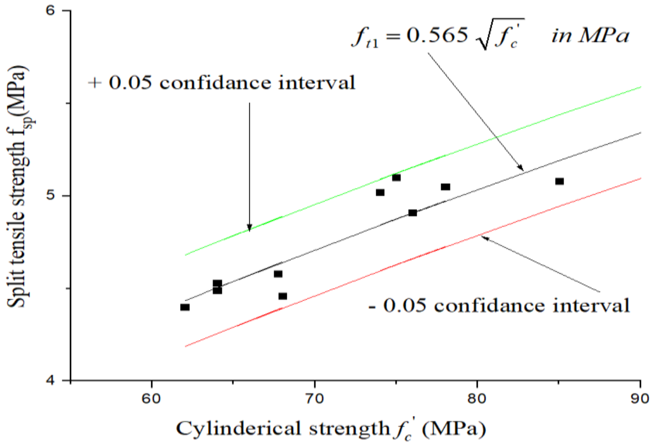

Fig. 12 Relation between cylindrical strength and split tensile strength of HPC

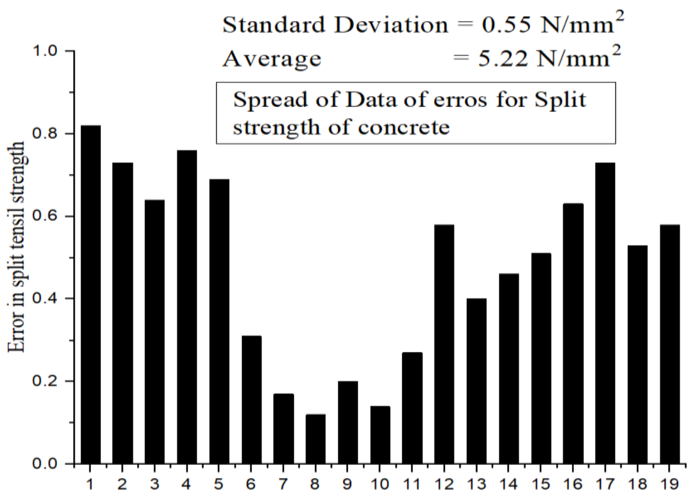

Fig.13 Relation between cylindrical strength of concrete and split tensile strength and error bars to indicate spread of data

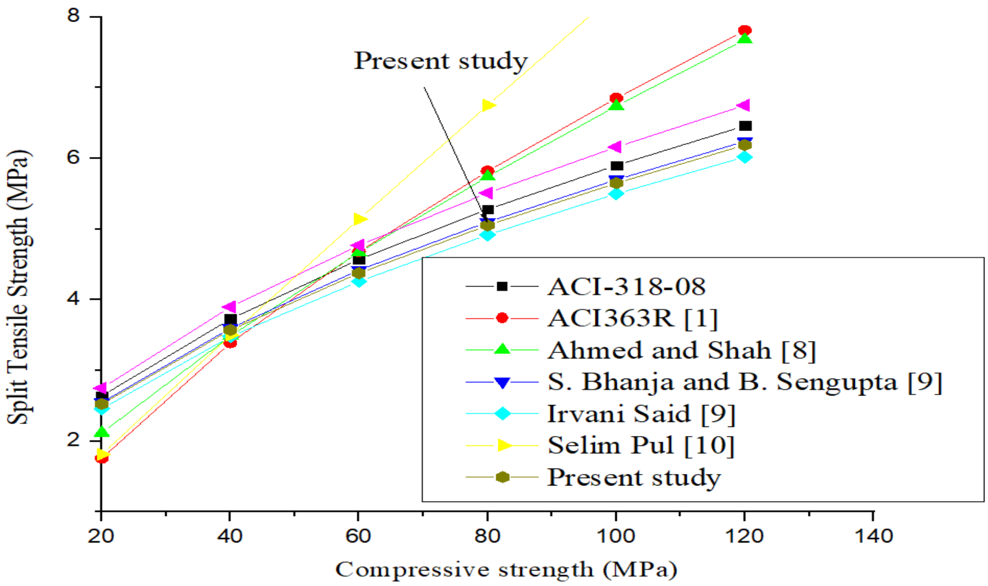

Fig.14 Comparison of analytical equations for split tensile strength

5.3.2. Modulus of rupture

The modulus of rupture (extreme fibre stress in bending) is affected by beam size and loading technique. The middle point loading and third-point loading are the loading processes used to determine flexure tension. Below the loading point with the greatest bending moment, the maximum fibre stress will occur. When dealing with symmetrical two-point loading scenarios, a critical fracture could arise at any point lacking the requisite strength to withstand the stress within the central third of the structure. It is to be expected that two-point loading would yield a modulus of rupture value lower than that observed in central point loading. This testing configuration is visually depicted in Fig. 15, in accordance with the guidelines outlined in IS 516-1959 [126].

Fig. 15 Modulus of rupture test with flexure crack near the centre of beam

Fig. 16 and Fig. 17 show the flexural tensile strength results. The flexural strength relationships are obtained by using regression analysis, as illustrated below.

$$f_{r1} = 0.946\sqrt{f_c'}\, in MPa \qquad .... \qquad (5.3)$$

$$f_{r2} = 0.90\sqrt{f_{cu}}\, in MPa \qquad .... \qquad (5.4)$$

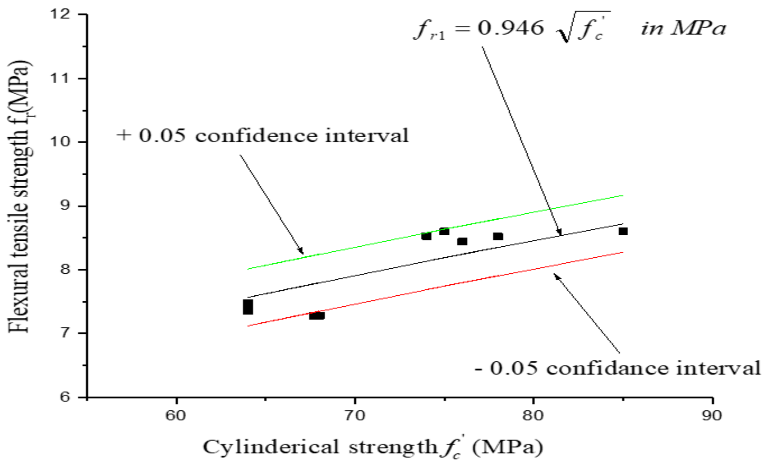

Fig. 16 Relation between cylindrical strength Flexural tensile strength of HPC

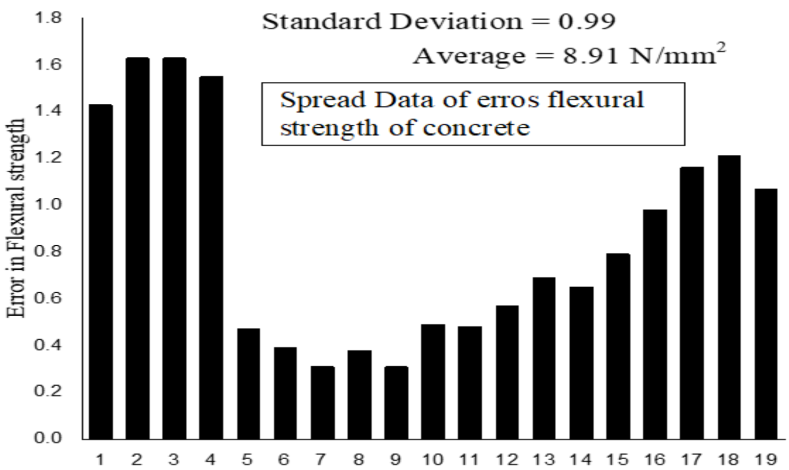

Fig. 17 Relation between compressive strength of concrete and flexure tensile strength and error bars to indicate spread of data

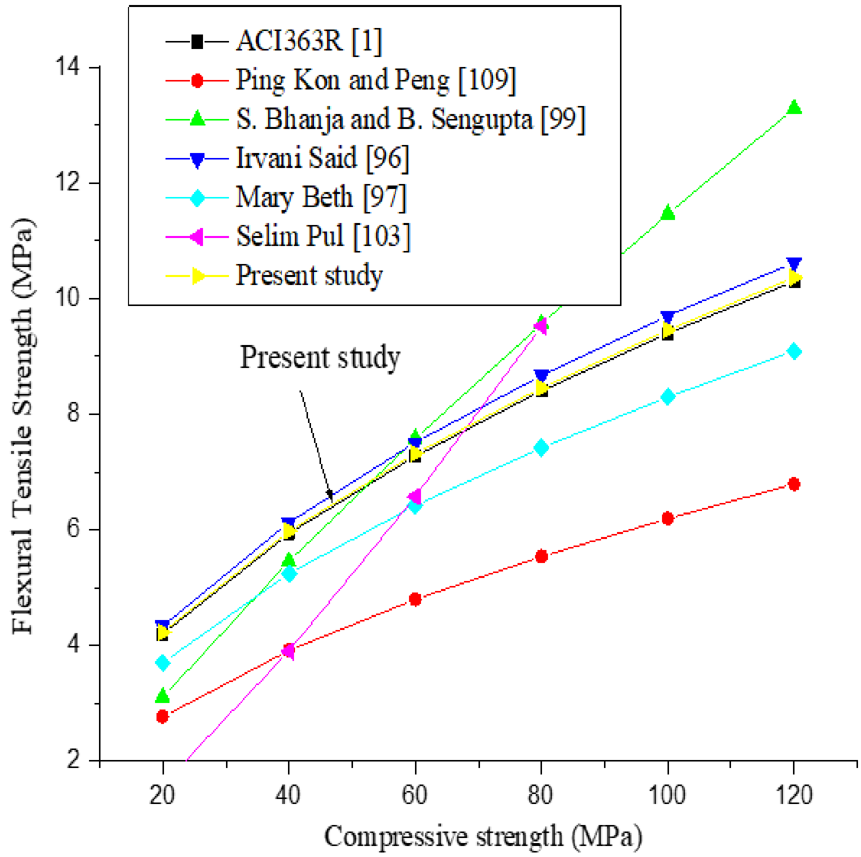

Fig. 18 Comparison of analytical equations for flexure tensile strength

As shown in Fig. 18, the current data is compared to Eq.5.3 using the analytical equations presented by Ping Kon and Peng [22], S. Bhanja and B. Sengupta [8], Irvani Said [19], Mary Beth [27], and Selim Pul [28]. The current study equation is completely in line with ACI 363 [3] and is similar to the equation suggested by Irvani Said [19]. The modulus of rupture is overestimated in the equations of Ping Kon and Peng [22] and Mary Beth [37]. S. Bhanja and B. Sengupta's [8] equation underestimates flexure tensile strength at low strength levels and overestimates at high strength levels. Selim Pul's [28] equation does not agree with any of the equations in the literature.

5.4 Modulus of elasticity of concrete

As shown in Fig. 19, stress-strain curves have been generated for various concrete strengths. Elasticity moduli are assessed at 40% stress level and are shown in Table 10. Regression analysis of the current study's data shows the following relationship for Ec.

$$E_{c1} = 5050\sqrt{f_c'} in MPa \quad .... \quad (5.5)$$

$$E_{c2} = 4800\sqrt{f_{cu}} in MPa \quad .... \quad (5.6)$$

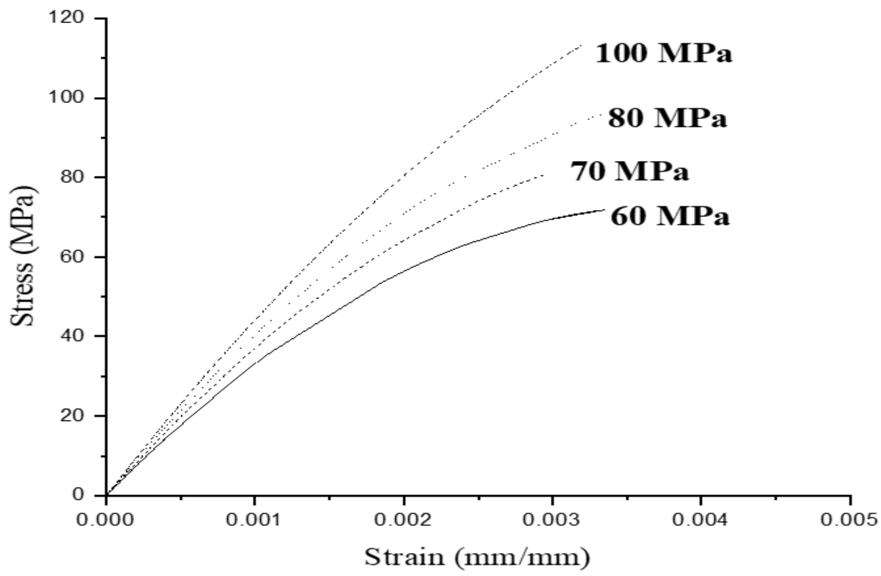

Fig.19 Stress-strain relationships in uni-axial compression

The relationship between the elastic modulus (Ec) of each specimen and the concrete strength (fc') is graphically illustrated in Fig. 20. Recognizing the significant impact of concrete strength on the modulus of elasticity, multiple endeavours have been undertaken to establish a correlation between these two parameters. Fig. 21 shows 211 data points from the literature. 39 Wee [38] data (40–125 MPa), 48 Gesoglu [16] data (60–100 MPa), 37 Ozuturan [35] data (14–47 MPa), 36 Turan [35] data (20–30 MPa), 25 Said Irvani [19] data (60–120 MPa.

Table 10 Experimental Values of modulus of elasticity and Poisson's ratio

Grade of Concrete in MPa	Cube Strength f_{cu} in N/mm^2	Cylindrical Strength f_c' in N/mm^2	Elastic Modulus E_c in GPa	Peak/ Ultimate Strain in mm/mm	Poisson's ratio
60	75.83	62.00	40.40	0.0023	0.187
60	73.86	70.90	41.84	0.0028	0.198
60	76.51	68.00	40.20	0.0027	0.159
60	74.10	65.00	40.43	0.0026	0.146
60	77.63	74.71	38.18	0.0024	0.185
70	78.85	75.58	42.42	0.0025	0.155
70	79.65	74.00	42.05	0.0026	0.154
70	79.35	74.36	43.47	0.0026	0.162
70	80.89	75.00	43.61	0.0027	0.167
70	80.87	73.00	43.97	0.0027	0.165
80	83.85	77.58	45.42	0.0030	0.135
80	93.65	88.00	45.05	0.0026	0.154
80	82.35	74.36	45.47	0.0027	0.182
80	88.89	78.00	44.61	0.0030	0.196
80	90.87	82.00	45.27	0.0029	0.165

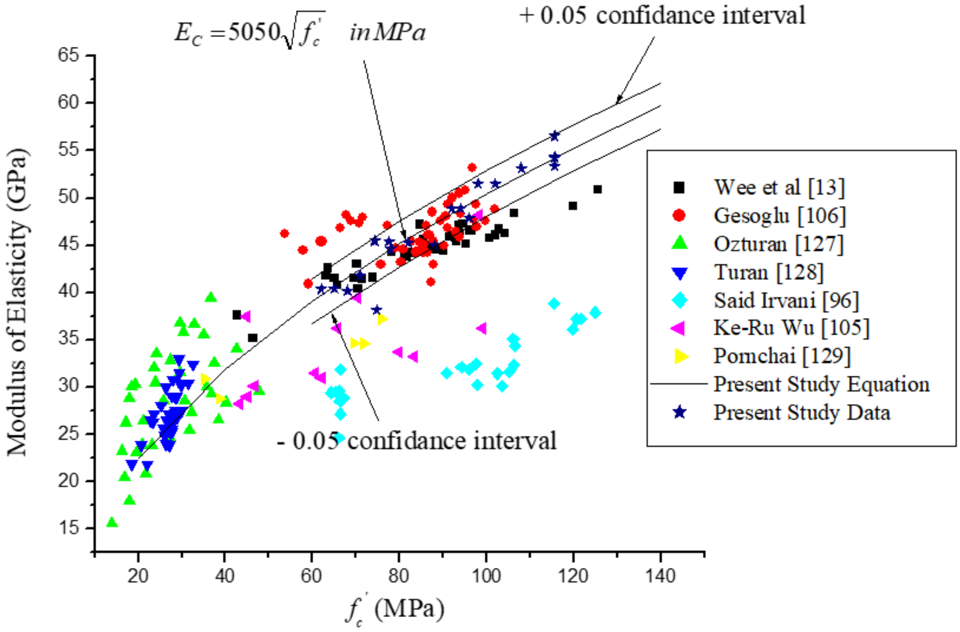

Fig.20 Values of elastic modulus of present research and others in the literature

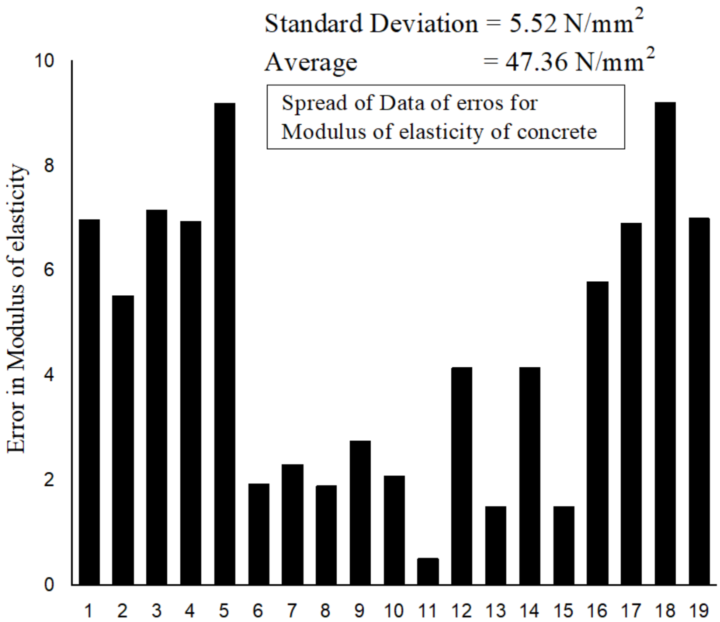

Fig.21. Error bars to indicate the spread of data

Ec values obtained in the present study range from 40 and 50 GPa. Table 11 shows some of the equations given for Ec by codes and researchers. When compared to other equations, the current study equation perfectly matches that proposed in CSA 23.3-94. IS 456-2000's equations overestimate the modulus of elasticity.

Table 11. Equations for modulus of elasticity by codes and researchers

Sr. No.	Researchers Name/ Code	Equation suggested
01	Euro Code 2	$E_c = 21500\left[\frac{f_c'}{10}\right]^{\frac{1}{3}}$
02	Gardener	$E_c = 3500 + 4300\sqrt{f_c'}$

Sr. No.	Researchers Name/ Code	Equation suggested
03	ACI 363 [3]	$E_c = 6900 + 3300\sqrt{f_c'}$ 21 MPa< f_c'< 83MPa
04	CSA 23.3-94	$E_c = 5050\sqrt{f_c'}$
05	Mary Beth et al.	$E_c = 5230\sqrt{f_c'}$ 40MPa< f_c'<90MPa
06	IS 456-2000 [20]	$E_c = 5000\sqrt{f_{ck}}$ f_{ck} is characteristic strength of concrete

5.5 Poisson's ratio

The cubes were tested to determine Poisson's ratios. Micro cracking begins to develop parallel to the direction of stress at higher stress levels. Transverse strain increases as the stress increases. Poisson's ratio rapidly increases near maximum strength until failure occurs. As a result, at 40% axial stress, the Poisson's ratio is determined, which corresponds to the point at which the elastic modulus is estimated. Table 11 displays the results of the current investigation. The non-evaluation of Poisson's ratio for 120 MPa concrete is attributed to the challenges arising from the intricacies of instrumenting specimens sized at 100 mm x 100 mm x 100 mm. Additionally, the constrained availability of pi-gauges featuring a gauge length of 50 mm further contributes to the unaddressed status of this parameter. For concrete strengths of 60 MPa, 70 MPa, and 80 MPa, the Poisson's ratio average values are 0.175, 0.166, and 0.153, respectively. Fig. 22 shows the findings of this study as well as those of other investigators, including Carrasquillo [11], Said Irvani [19], and Mertol et al. [27]. While a definitive trend for Poisson's ratio may not be apparent, the findings of the present study suggest that an enhancement in concrete strength correlates with a reduction in the average value of Poisson's ratio.

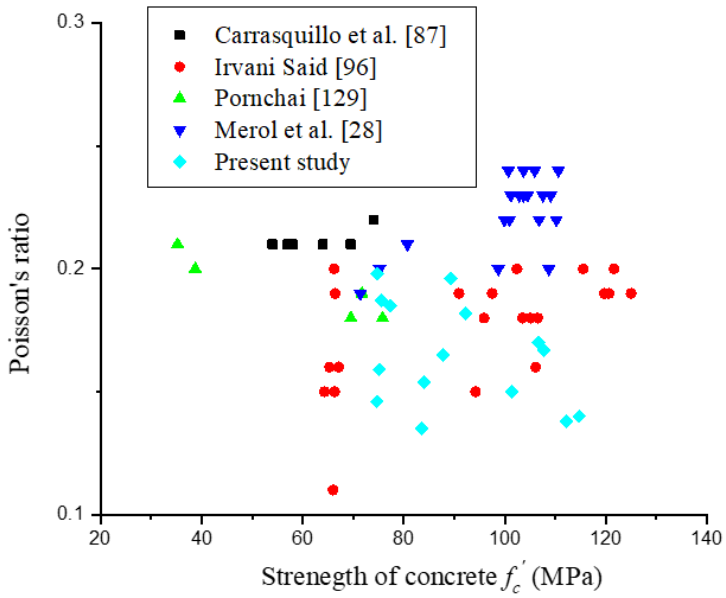

Fig. 22 Values of Poisson's ratio of the present study and other researchers

6. CONCLUSION:

Study of some mechanical properties is also important for design of reinforced concrete members. This chapter finds some mechanical properties of HPC, such as compressive strength, split tensile strength, flexure tensile strength and modulus of elasticity. Based on the experimental data of present study, analytical equations are proposed for the above. The proposed analytical equations are compared with the equations in the literature and codes and their suitability was discussed.

i. It is investigated that including new materials and improving mix proportions have a significant impact on the enhancement of the mechanical properties of concrete. When compared to ordinary concrete, the greater compressive strength, flexural strength, and durability observed in HPC highlight its ability to withstand significant loads and resist damage to the environment over an extended service life.

ii. The addition of various extra cementitious materials, such as fly ash, slag, and silica fume, has not only improved the concrete's mechanical properties but also demonstrated the ability to reduce the environmental effect of traditional concrete manufacturing. This environmentally beneficial component of HPC corresponds effectively with the developing perspective of eco-friendly construction practices.
iii. It has been proposed to maintain the ultimate concrete strain constant at 0.003 in line with ACI 318 (2008).
iv. The present study also proposes a capacity reduction factor for columns in concentric compression and stress-block parameters for HPC in relation to the cube compressive strength of concrete.
v. The error analysis shows the consistent conservativeness of the proposed NSC and HPC parameters.
vi. The split tensile strength, flexural strength, and modulus of elasticity of concrete demonstrate a correlation with its compressive strength and exhibit favourable agreement with numerous formulae proposed in the existing literature.
vii. The average Poisson's ratio obtained for concrete strengths ranging from 60 to 80 MPa is 0.165.

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